Office of Water &
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September 1978

An Evaluation of the Resource Recovery Demonstration Project, Baltimore, Maryland

Executive Summary

AN EVALUATION OF THE RESOURCE RECOVERY DEMONSTRATION PROJECT, BALTIMORE, MARYLAND

Executive Summary

This report (SW-719) was prepared under contract for the Office of Solid Waste by A. J. Helmstetter and R. A. Haverland

U.S. ENVIRONMENTAL PROTECTION AGENCY

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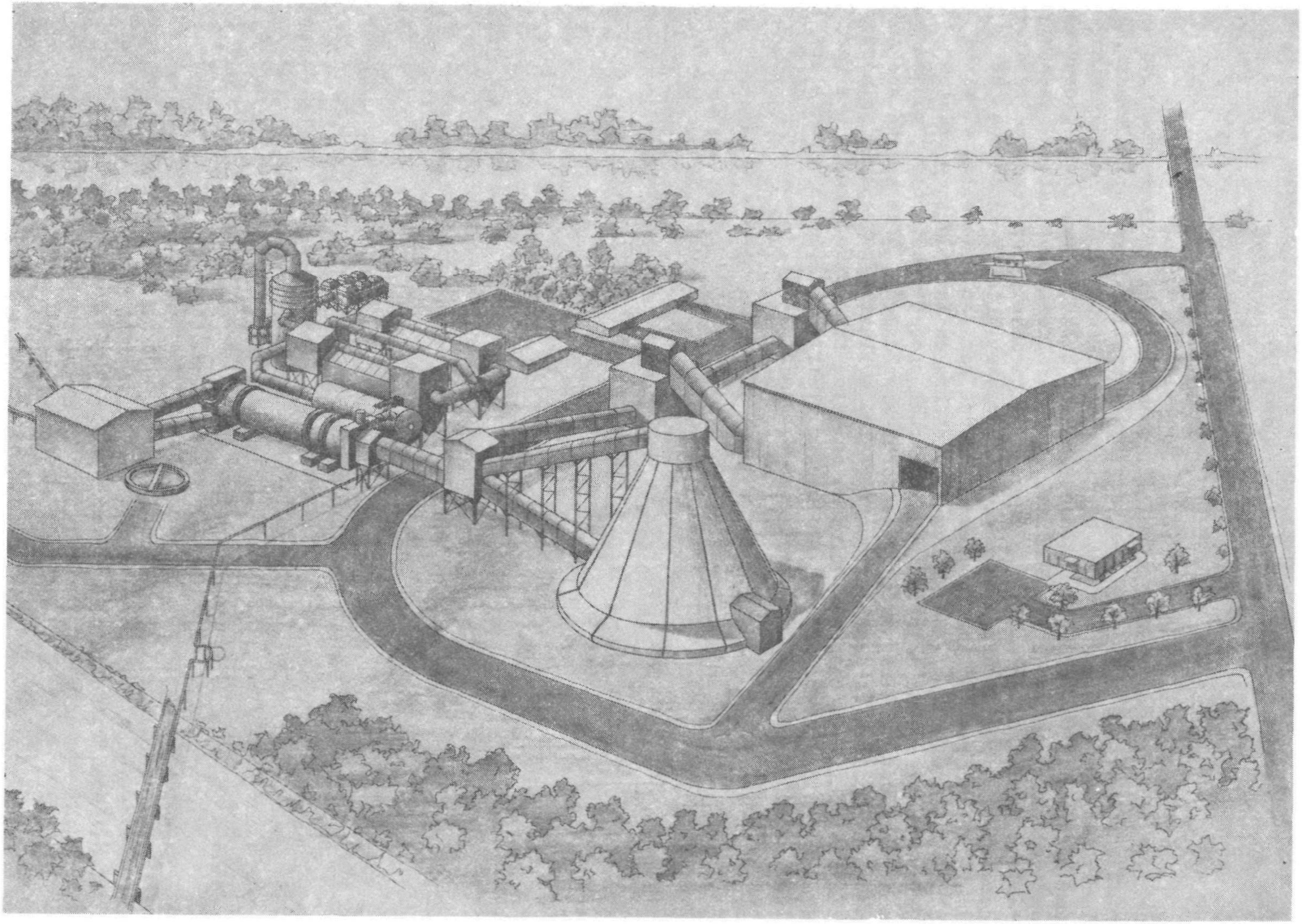
PREFACE

This report is a complete technical, economic, and environmental evaluation of the Landgard® Resource Recovery Demonstration Plant at Baltimore, Maryland. It was prepared for EPA by A. J. Helmstetter and R. A. Haverland of Systems Technology Corporation. Because of its bulk the report is presented in four volumes: an Executive Summary, the operational evaluation, an analysis of problems, and the appendices. Intended particularly for resource recovery planners and administrators, the Executive Summary briefly describes the Baltimore application of the Landgard® concept for the processing of mixed municipal solid waste. In addition, it presents an introductory problem analysis of most of the major innovations that proved ineffective, caused serious shutdowns, and required redesign or abandonment. The second and third volumes are detailed in-depth accounts of the evaluation, prepared primarily for the designer. Of the four volumes, only the Executive Summary has been prepared for wide distribution. The second, third, and fourth volumes are available through the NTIS, Springfield, Virginia 22161.



BALTIMORE LANDGARD® FACILITY

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LIST OF UNIT CONVERSIONS

Description	SI		English Equivalents	
	Unit	Symbol	Unit	Symbol
Length	meter	(m)	3.28 feet	(ft)
	centimeter	(cm)	0.394 inches	(in)
	millimeter	(mm)	0.039 inches	(in)
	micrometer	(μm)	1.0 micron	(μ)
Area	square meter	(m^2)	1.76 square feet	(ft^2)
Volume	cubic meter	(m^3)	35.31 cubic feet	(ft^3)
	liter	(l)	0.264 gallons	(gal)
Mass	kilogram	(kg)	2.20 pounds	(lbs.)
	megagrams	(Mg)	1.10 tons	(ton)
Pressure	kilopascal	(kPa)	0.145 pounds per square inch	(lbs./in^2)
Temperature	celsius	(C)	5 Fahrenheit/9-17.8	(F)
Energy	joule	(J)	9.48×10^{-4}	(Btu)
Density		(kg/m^3)	.0624	(lbs./ft^3)
Energy/Mass		(MJ/kg)	431	(Btu/lb.)
Mass Loading		(g/DSCM)	0.437	(gr/DSCF)
Concentration		(μl/l)	1.0	(ppm)

ACKNOWLEDGEMENT

This evaluation program was performed under EPA Contract No. 68-01-4359, "Technical and Economic Evaluation of the EPA Demonstration Resource Recovery Project in Baltimore, Maryland."

The EPA Project Officer was David B. Sussman of the Office of Solid Waste, Washington, D.C.

Testing was carried out at the demonstration facility in Baltimore, Maryland, with the cooperation of the city plant staff and the Monsanto on-site engineering staff. The economic evaluation was performed in conjunction with Arthur Young & Company. The contribution of both of these groups has been greatly appreciated. The contribution of Dr. H. G. Rigo along with other staff members is also acknowledged.

Systems Technology Corporation would like to express its gratitude to the above-named individuals and all others associated with this evaluation.

SECTION 1

EXECUTIVE SUMMARY

INTRODUCTION

The demonstration of the Landgard® resource recovery concept in Baltimore, Maryland was one of the first attempts in this country at large scale resource recovery from mixed municipal solid waste. Partially funded by grants from the U.S. Environmental Protection Agency (EPA) and the Maryland Environmental Services, the plant was designed by Monsanto EnviroChem for the City of Baltimore to demonstrate the feasibility of using pyrolysis as an integral phase in the recovery of energy, glassy aggregate, and ferrous metals from a mixed municipal solid waste stream. The plant was designed to receive, shred, and pyrolyze 907 megagrams (1000 tons) per day of unsorted residential waste, recover the usable residues and energy from the processed waste, reduce the volume of material requiring ultimate disposal, and to perform these operations within all environmental standards.

To evaluate the operational experience of the Baltimore plant, the EPA commissioned SYSTECH to analyze the technical, environmental, and economic aspects of the plant. Consequently, a four-volume report was prepared by SYSTECH, which is intended to provide information that will assist others involved in implementing resource recovery plans. The four-volume report is available from the National Technical Information Service.

The single most important fact that must be understood concerning the Baltimore Landgard plant is that it was a demonstration of the application of a technology in a novel configuration, and that technical modifications in such a situation are not unusual in order to achieve effective operation. However, in the case of the Landgard demonstration, the modifications were extensive, costly, and satisfactory results were at times elusive. Nevertheless, contrary to common perceptions, the project has in many ways been a success. Not only did it provide invaluable experience in the use of innovative equipment combinations and techniques, but it also ultimately proved the feasibility of using the Landgard concept (though not the original design) to process mixed municipal solid waste.

Of major importance is the fact that the major processing component, the rotary processing kiln, has been demonstrated to be an excellent primary reaction vessel. Numerous operational deficiencies and abnormalities such as refractory failures, process instability, and control difficulties were encountered in the kiln operation during the early part of the demonstration. However, these problems have been effectively resolved by converting the kiln from a pyrolytic reactor to a substoichiometric combustion reactor (starved-

TABLE 1. CHRONOLOGY OF LANDGARD®

	Process Development
Fall 1968	- Bench scale prototype, Dayton, Ohio .3 to .6 TPD capacity
Spring 1969	- Small scale prototype, St. Louis, Missouri 35 TPD capacity
Spring 1974	- Small scale prototype, Kobe City, Japan 35 TPD capacity
Nov. 1974	- Full scale prototype, Baltimore, Maryland 1,000 TPD capacity
	Baltimore Demonstration
Sept. 8, 1972	- EPA grant awarded
Jan. 10, 1973	- Contract approved
Jan. 31, 1975	- Construction completed, plant commissioned
Nov. 1, 1975	- Plant could not meet guarantees--modifications required
Dec. 31, 1975	- Supplemental agreement for modifications signed
Jan. 1, 1976	- Modification work begun
Nov. 5, 1976	- Modifications completed
Nov. 6, 1976	- Operation begun
Jan. 31, 1977	- Monsanto recommends, project termination
Feb. 18, 1977	- Monsanto personnel leave site, city continues with project

air incinerator), replacing the installed kiln refractory with a different material and installation method, and modifying the method of air introduction and the amount of heat supplied by auxiliary fuel for the process. After the remedial provisions were implemented, there has been no downtime attributed to rotary kiln failure, and the long-term reliability of this component will be determined with continued operation.

The secondary processing equipment, consisting of the *gas purifier* (afterburner) and the pollution control device, is currently being redesigned to perform at acceptable levels of reliability. The *gas purifier*, which is presently operated in a slagging mode, will be redesigned to operate in a more conventional non slagging mode. The existing wet scrubber, used to control stack emissions, is being replaced with a dry electrostatic precipitator of the type proven successful in many solid waste incinerators and coal-fired boilers. Other operational deficiencies and abnormalities were generally due to mechanical failures typical of a new facility. Such problems have been or will be eliminated by available engineering expertise or by installing other standard equipment.

In summary, although the current plant configuration and operation differs appreciably from that specified in the original design concept, it appears that the plant can operate successfully. Long-term operation under the new design conditions is planned by the City of Baltimore. However, it should be understood that this system is not now offered commercially by the Monsanto Company, and the technical and economic parameters under the new design have not yet been documented in continuous operation.

BACKGROUND

In 1967, Monsanto EnviroChem began developing solid waste processing for commercial applications and subsequently determined that direct pyrolysis as an integral operation in solid waste disposal warranted further development with corporate financing. During early 1969, Monsanto conceived the Landgard process and accordingly designed and fabricated a 0.5 Mg per day [0.6 tons per day (tpd)] bench-scale unit with a 0.3 meter (1 foot) diameter by 1.5 meter (5 feet) long kiln which was operated and tested in Dayton, Ohio. The results were so encouraging that by June 1969 a 32 Mg per day (35 tpd) prototype kiln, 1.2 meters (4 feet) in diameter by 6.1 meters (20 feet) long was operating in St. Louis, Missouri. Another kiln, a 32 Mg per day (35 tpd) unit was placed in operation in Kobe City, Japan, by Kawasaki Industries, a licensee of the Landgard process. Based upon the experience with these units, the Baltimore project began in late 1972 with ground breaking in January 1973 (table 1). Since the completion of the Baltimore plant in January 1975, the plant mechanical and control debugging has been a progressive on going task.

Because of the many changes in the continuing evolvement of the Baltimore plant, this report discusses the plant configuration and operations as they were between November, 1976 and June, 1977 when onsite SYSTECH personnel monitored the plant operation. Consequently, the plant discussed differs from that prescribed in the original design and will differ from the final plant configuration and operation. The four-volume evaluation report documents the plant modifications to date with an explanation of them and presents alternative plant configurations to exploit the potential of the Landgard concept, as well as to profit by the experience gained thus far.

PLANT EVALUATION

As prescribed by the EPA in the contractual award to SYSTECH for the evaluation of the Baltimore plant, the following requirements have been met:

1. Description of the initial plant processing configuration;
2. Determination of the process balance and efficiency;
3. Assessment of the effects of the process on the environment;
4. Summary of the proposed and implemented modifications to improve the process performance and reliability;
5. Detailing of the proposed and implemented modifications to improve the process performance and reliability;
6. Assessment of the current cost to process waste with the Landgard process and the projected cost when all modifications will be completed, with the assumption that the modifications will produce the desired improvements.

Process Description

The Landgard process is based and centered on the pyrolysis of shredded municipal solid waste and the subsequent *in situ* combustion of the pyrolysis products. Figures 1 and 2 show the basic layout of the Baltimore Landgard Plant where the principal components are a rotary kiln, the primary reaction vessel, and a *gas purifier*, the secondary reaction vessel. Figures 3 through 7 show details of the major equipment components.

After the incoming waste is weighed, deposited, and shredded* (figure 3) it is fed at a controlled rate to hydraulic ram feeders (figure 5) which in turn feed the shredded waste to the rotary kiln (figure 6). Since the kiln operates at a negative pressure (minus one inch of water), the ram feeders extrude the waste through passage-restricted cylindrical tubes to maintain the kiln air seal. As the waste tumbles down the declined rotating kiln, it undergoes various thermal processes and reactions. While the partially combusted gases, called the kiln-off gases, exit at the feed end of the kiln to flow to the *gas purifier* (figure 7), the combustion residue, consisting of ash, other inert solids, and some unburned carbon char, is discharged at the other end of the kiln to fall into a water quench tank.

The thermal processing begins when the shredded waste is extruded into the hot rotary kiln. As the waste continuously tumbles down the kiln, it is dried and its volatile content is vaporized to form a gas mixture containing carbon monoxide, hydrogen, methane, and other hydrocarbons, along with inert dilutents. This gas is partially combusted in the kiln, with the heat release limited to the exact level needed to sustain the endothermic pyrolysis

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* Originally it was then discharged into a storage and recovery silo (figure 4).

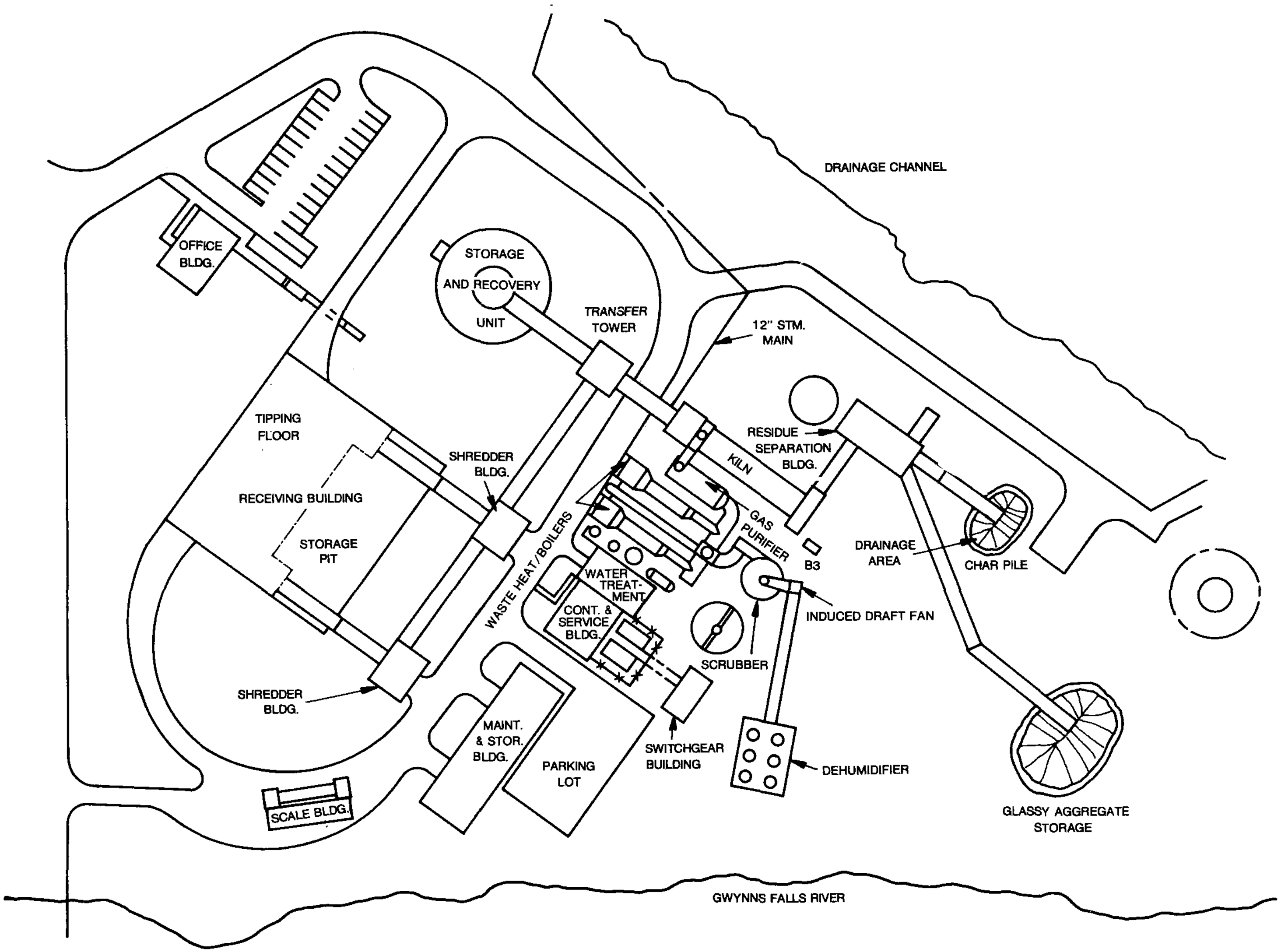

Figure 1. A plan view of the Baltimore Landgard® facility.

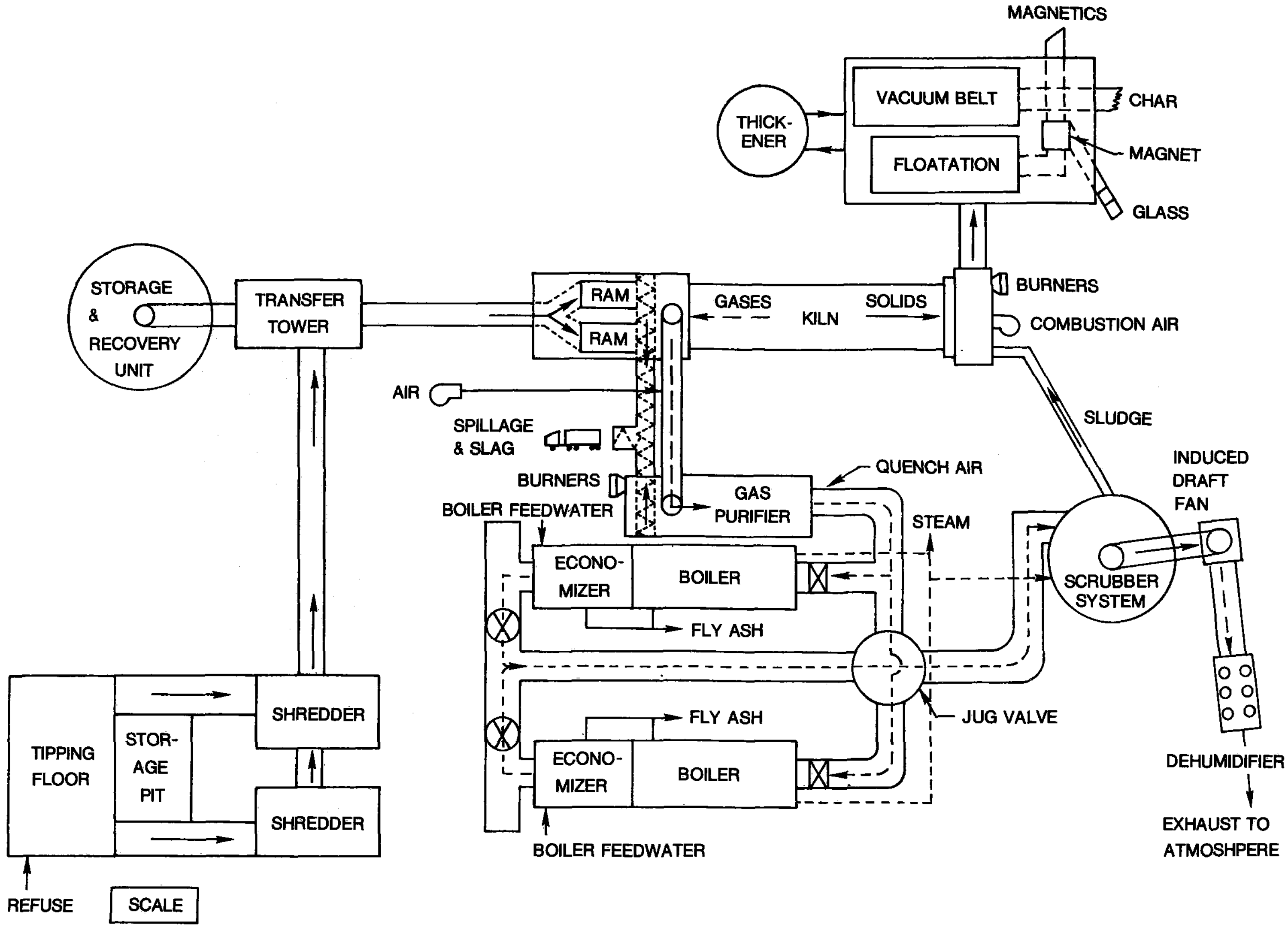

Figure 2. Process flow diagram of the Baltimore Landgard® facility.

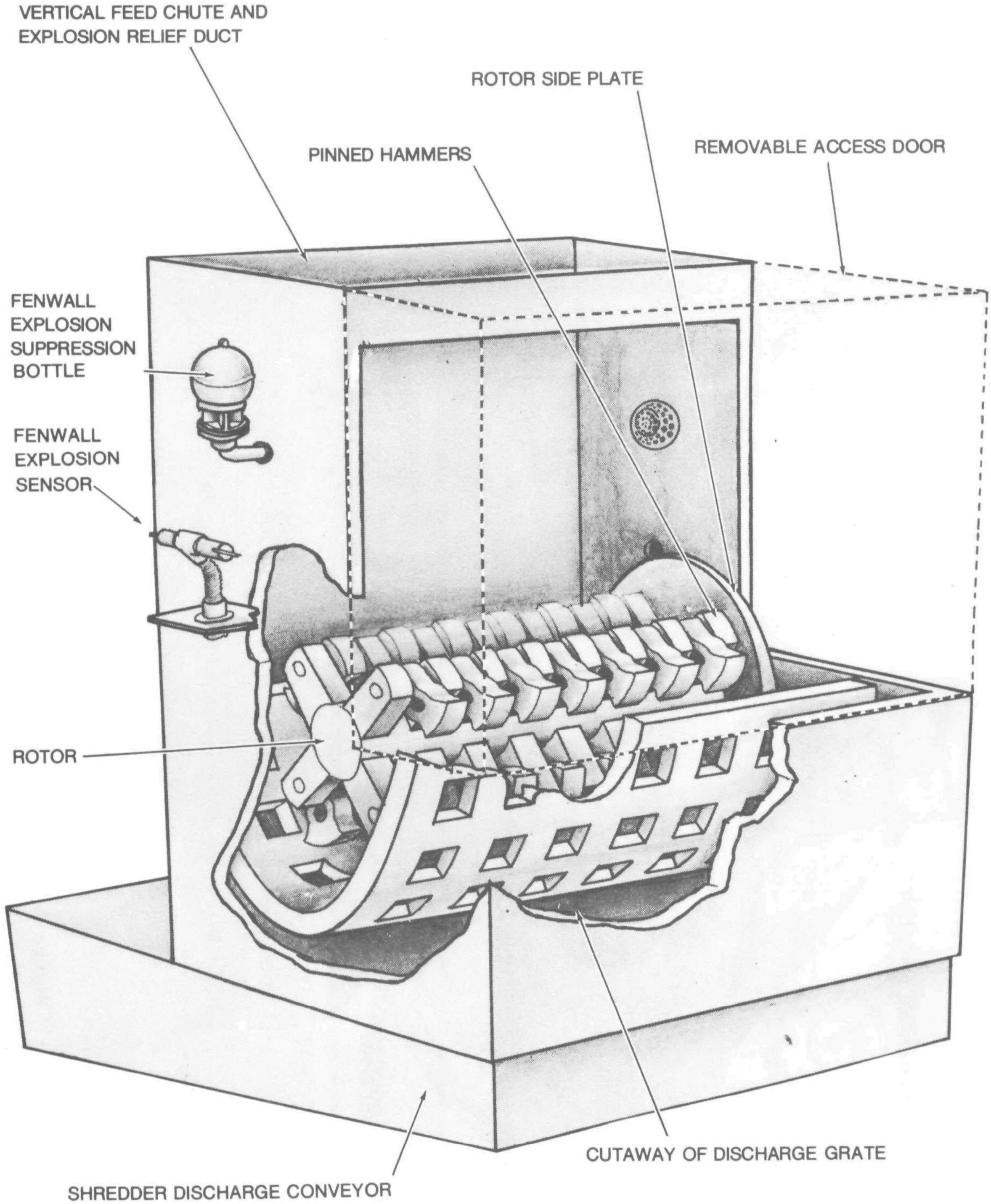

Figure 3. Schematic of a hammermill shredder.

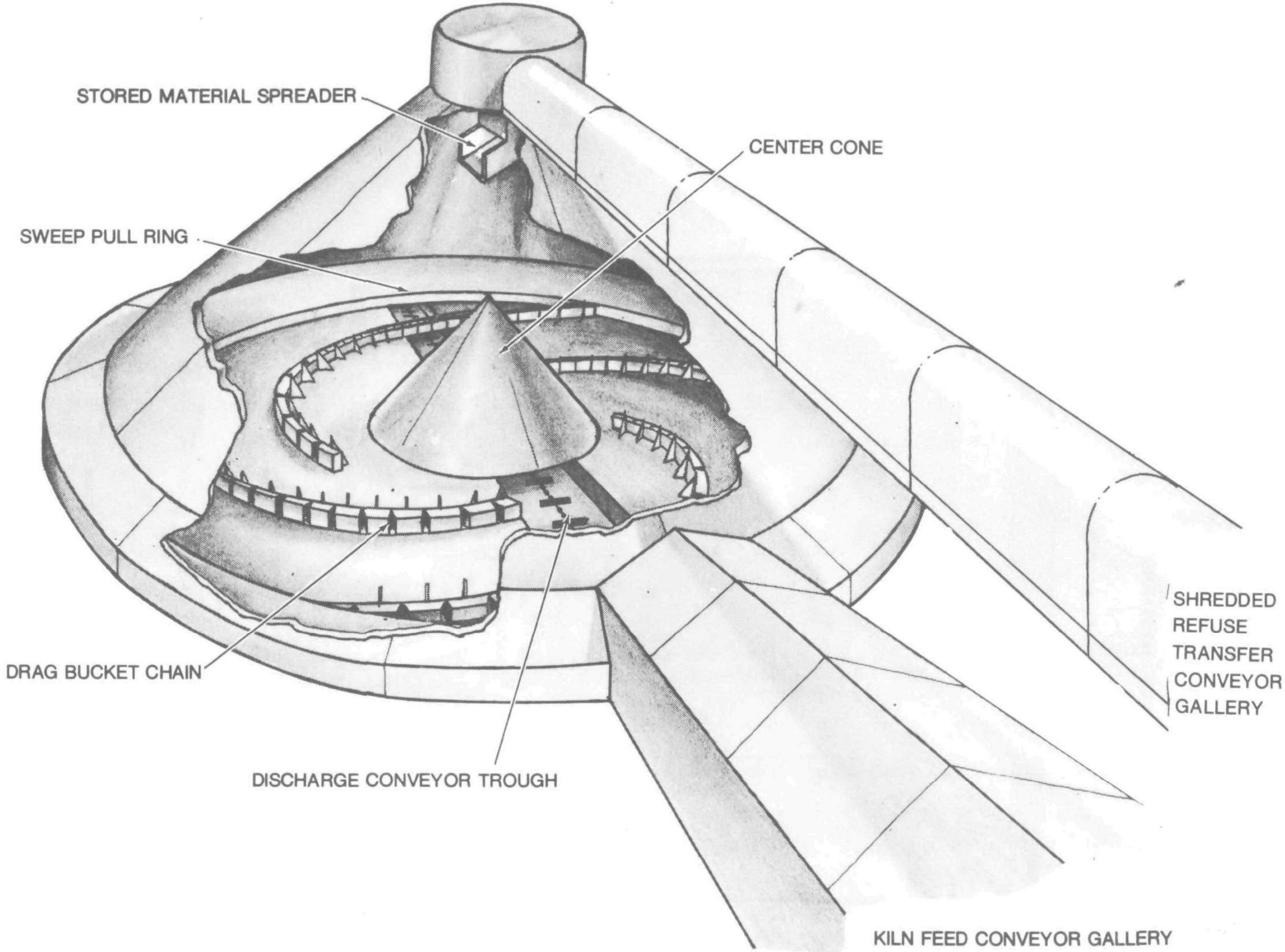

Figure 4. Schematic of the storage and recovery unit.

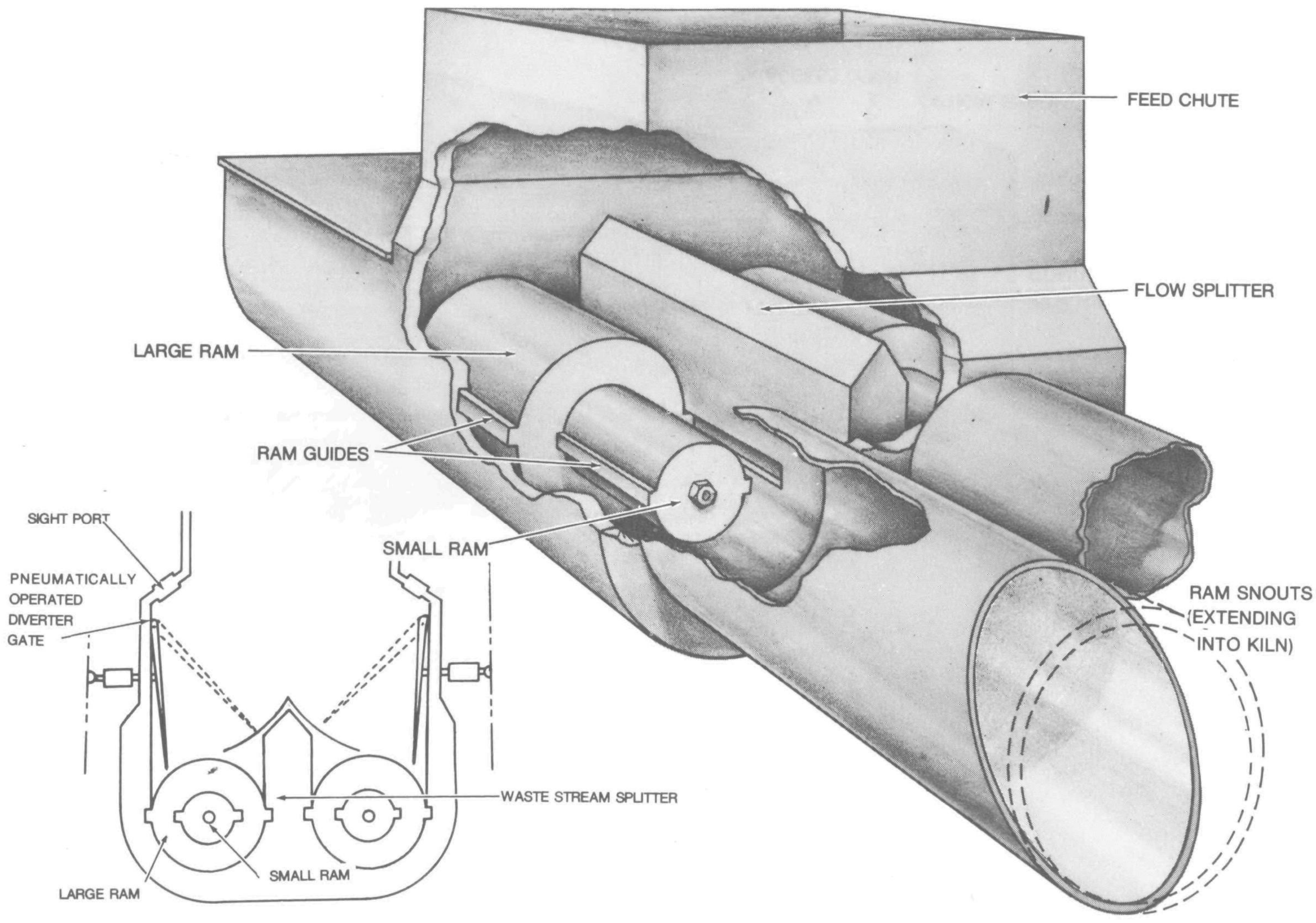

Figure 5. Schematic of the ram feeders.

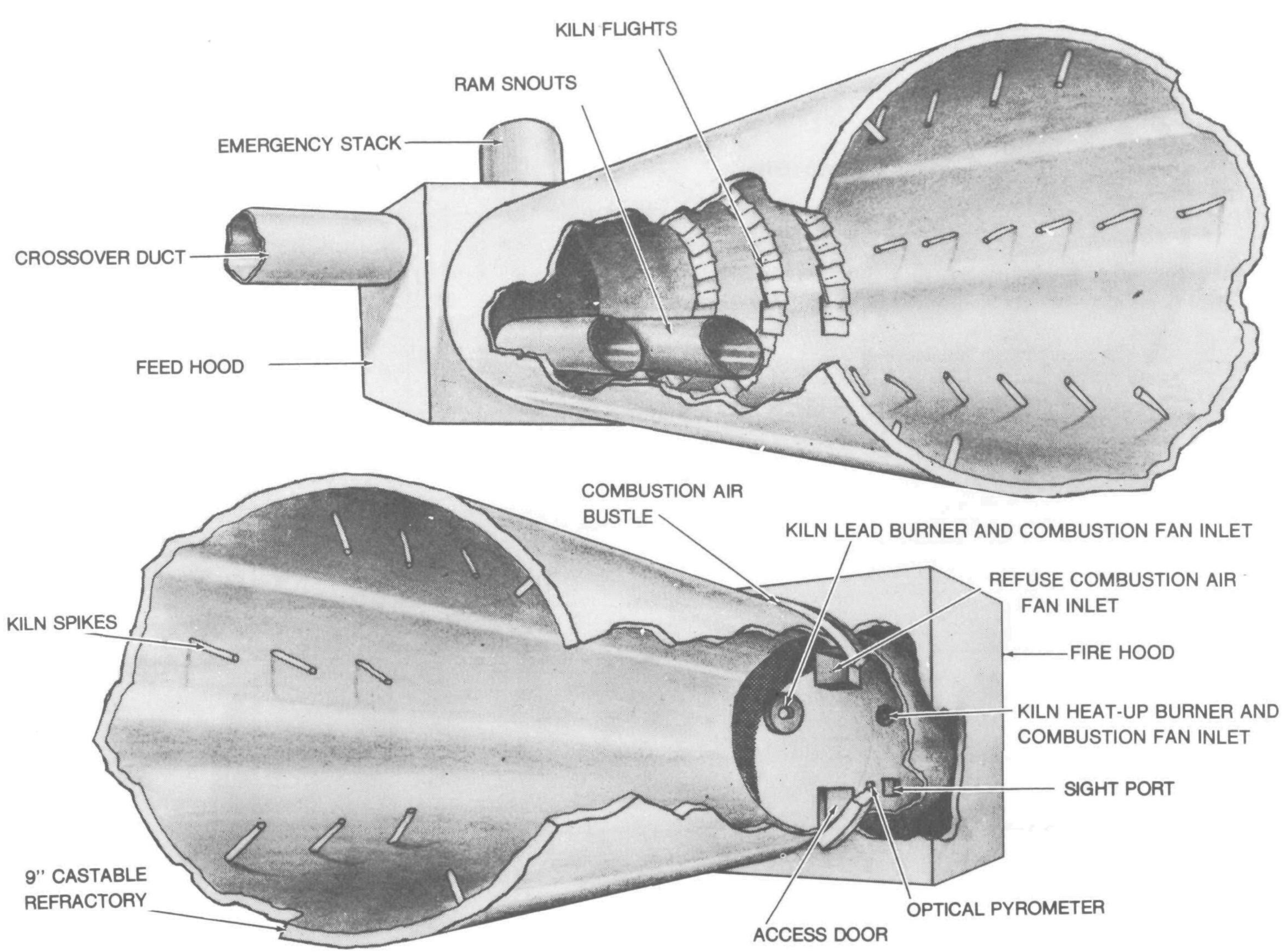

Figure 6. Schematic of the kiln.

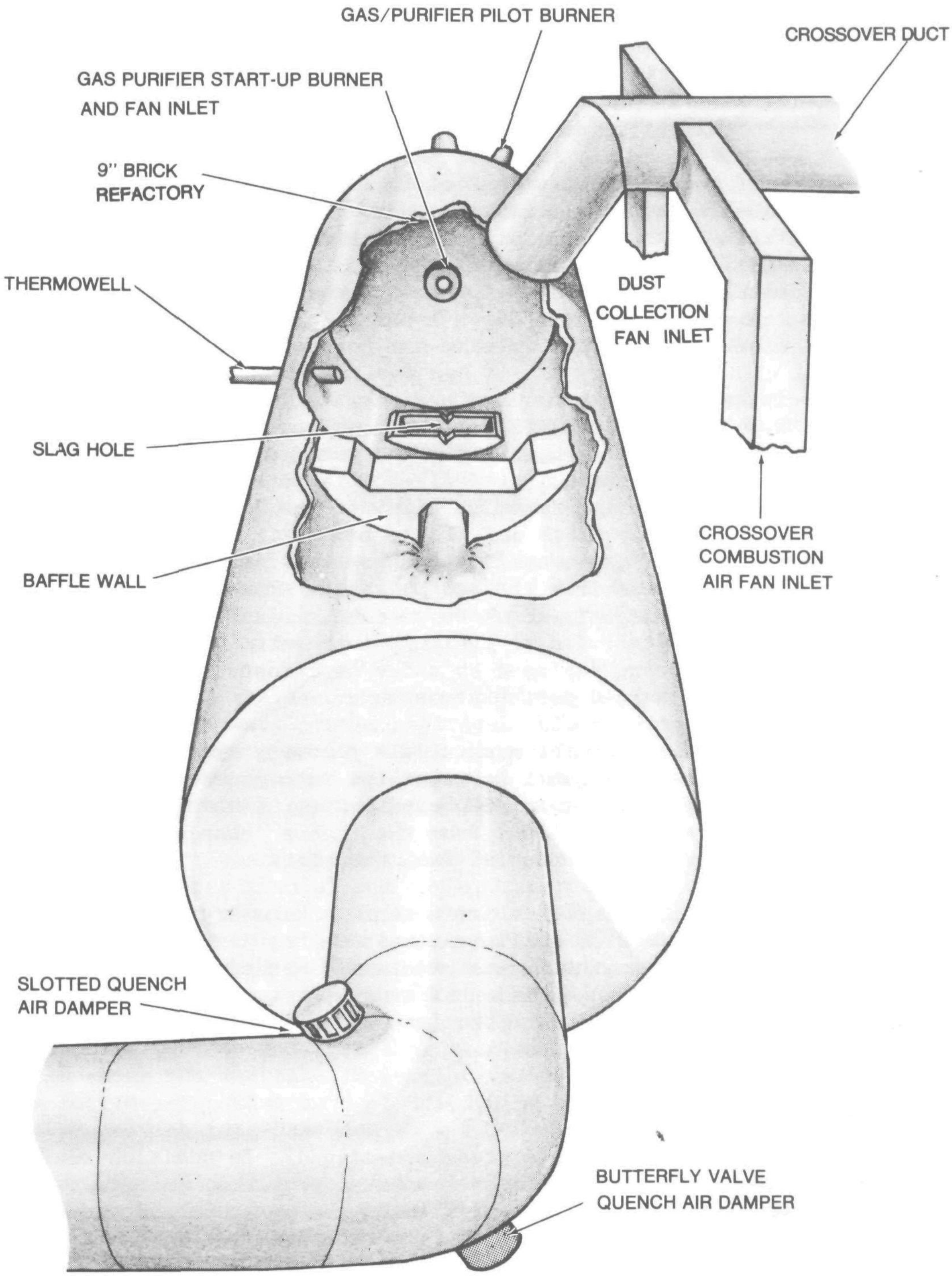

Figure 7. Schematic of the gas purifier.

reaction. The combustion takes place under substoichiometric conditions which are maintained by carefully controlling the airflow into the kiln. When approximately 40 percent of the theoretical combustion air is supplied, the thermal reactions become self-sustaining and therefore do not need the supplemental heat from the kiln burners. Since oxidation occurs in the thermal reaction zone, the kiln is not a pure pyrolytic reactor, as originally conceived, but rather a substoichiometric combustion reactor like a starved-air incinerator.

As the kiln-off gases are drawn out of the kiln feed hood by the induced draft fan, the kiln-off gas enters the *gas purifier* tangentially, producing a cyclonic flow pattern in that vessel. Then, with air supplied to the *gas purifier*, the remaining pyrolysis products, carbon and soot entrained in the gas stream are combusted completely. During the combustion process the cyclonic flow pattern throws molten fly ash particles to the vessel side walls from where they flow to a slag tap hole in the bottom of the *gas purifier*.

The pyrolysis gas mixture generated and partially burned in the kiln has a fuel value of 816 J/SCM (90 Btu/SCF) and is completely combusted in the *gas purifier*. While the gas stream exiting the *gas purifier* has a relatively low particulate content, the amount of particulate is a function of the quantity and size of the particles in the incoming kiln-off gas.

Heat recovery from the gases exiting the gas purifier takes place in two waste heat boilers downstream from the *gas purifier*. These boilers have a heat recovery efficiency slightly above 80 percent. Finally, the flue gases are drawn by the induced draft fan to the emission control device, originally a wet scrubber which is being replaced by a dry electrostatic precipitator, and are subsequently discharged to the atmosphere.

The original design called for a materials recovery system where the solid residue exiting the kiln would be separated into magnetic metal, glass, and char fractions. This separation step used a water flotation tank to separate the heavies (metal and glass) from the lights (char and ash) and a magnet to separate the magnetic material from the glass.

However, the operation of the entire materials recovery system was discontinued because of the lack of sufficient manpower to adequately operate the materials recovery equipment, the lack of financing needed to improve the process reliability, and the insufficient financial return to justify the additional manpower and investment. Consequently, all solid residue is currently removed for landfill disposal.

Plant Performance

The Baltimore plant has not operated as designed. In addition to numerous engineering, operating, and developmental problems, the plant has failed to meet two of the standards specified in the agreement between the City of Baltimore and Monsanto. First, particulate loadings in the discharged stack gases were prescribed to be less than the Maryland standard of 0.07 grams per standard cubic meter (g/SCM) or 0.03 grains per standard cubic foot (gr/SCF) but have been about .28 g/SCM (.12 gr/SCF). Second, while the plant was guaranteed to have an 80 percent operational availability during a 60-day test run, the longest run thus far was only 25 days because of miscellaneous equipment failures.

Among the operational and equipment difficulties which adversely affected the plant reliability were kiln temperature control, residue in the kiln fusing into large slag agglomerations, refractory failures, fan and pump breakdowns, ram feeder jamming, slag tap hole plugging, and material handling and retrieval malfunctions. As a result of the foregoing, the cost of the facility increased and the plant demonstration sustained major delays. Many of the plant shortcomings have been due to the 30 times scaling from the 32 Mg per day (35 tpd) capacity of the prototype unit to the 907 Mg per day (1000 tpd) capacity of the Baltimore plant.

Moreover, the structure of the project administration during the demonstration hampered plant operations and thereby contributed to limiting the percentage of on-stream time of the plant. Under the original contract agreement Monsanto provided turnkey service during the plant demonstration, using city maintenance and operating personnel during the start-up and shakedown phases of the project. Not having the plant staff directly responsible to the contractor had the expected tendency to cause confusion regarding who should direct the efforts of the plant staff; the startup personnel, or City management personnel. During the supplemental agreement, Monsanto's role was changed to that of a contractor to the City not directly involved in plant operation. However, technical recommendations were made by Monsanto concerning plant operation during this period.

In addition to the uncertainties relating to the 30 times scale-up, the system designer had very little empirical information available on large-scale shredding, conveying, storing, and transporting of municipal solid waste. Consequently, the design for the material handling equipment had to be based primarily on theoretical estimates which proved to be overly optimistic.

The Baltimore plant was designed to handle a feed rate of 636 kg per minute (1,402 lb per minute) and can operate at rates as low as 303 kg per minute (668 lb per minute). While the plant has operated at the design rate, the total waste throughput has been considerably less than the design capacity because operational and equipment malfunctions have limited the total runtime and the average operational feed rate to only 455 to 530 kg per minute (1000 to 1170 lb per minute). However, plant performance has improved substantially subsequent to various modifications made to the plant by the City of Baltimore. Figure 8 shows the increase in cumulative throughput with time. In contrast to the design processing rate of 281,000 Mg per year (310,000 tpy), the actual annual processing rate has been only 65,000 Mg per year (71,000 tpy).

The numerous operational and equipment difficulties and deficiencies occurring during the demonstration have made it extremely difficult to characterize the process. Nevertheless, the process balances presented in this report, which are based on the measurements taken by onsite SYSTECH personnel from November 1976 through August 1977, are representative of the process stream quantities that prevailed throughout the demonstration. Of particular importance to the balance presentation is the variation in the process flows due to varying waste composition. Typically in processing systems handling

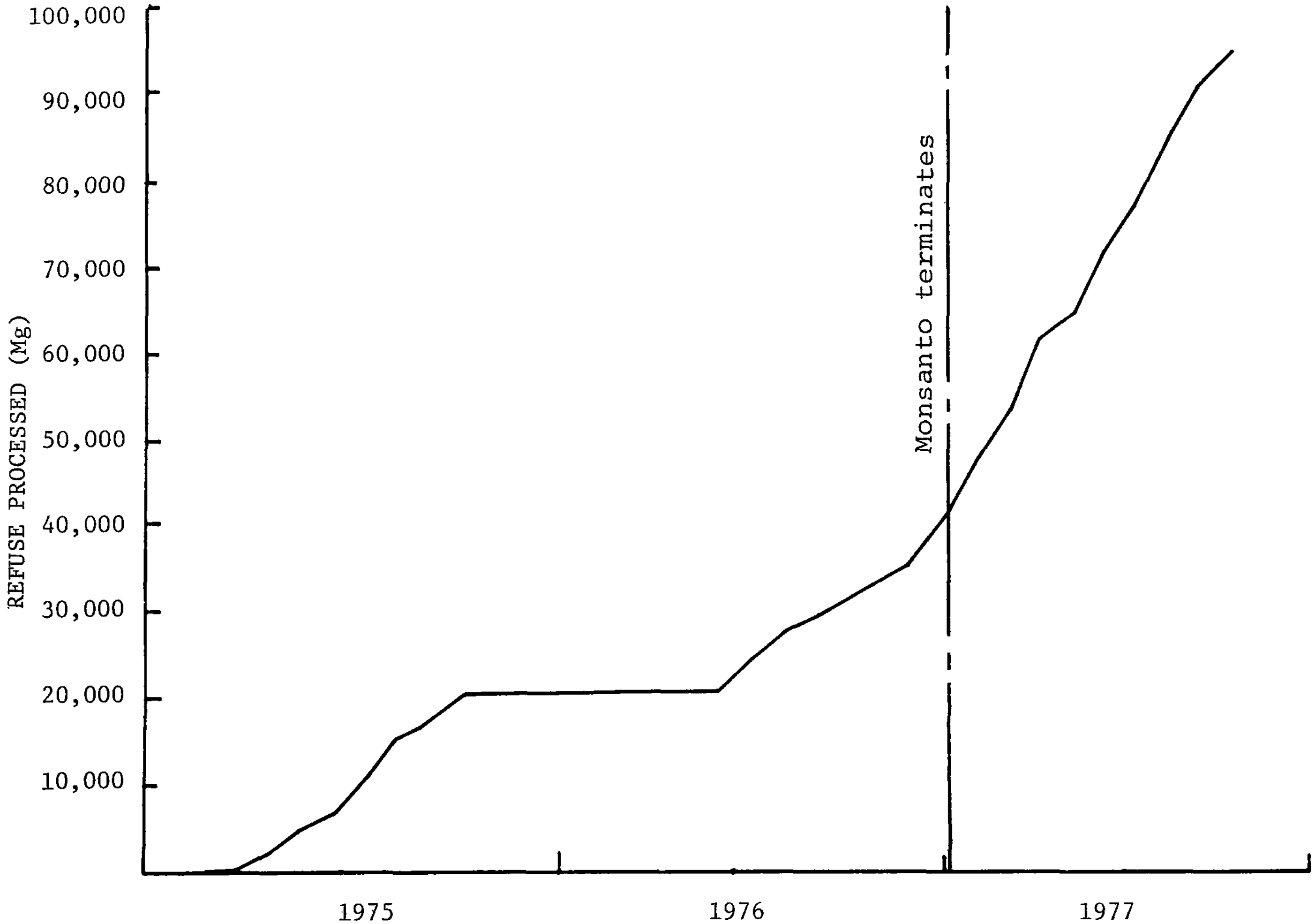

Figure 8. Plot of cumulative refuse processed over time.

mixed municipal solid waste, this variation makes efficient waste processing very difficult. Since municipal solid waste is not homogenous and has time-varying characteristics, the processing equipment must be designed to accommodate these variations.

Figures 9 and 10 show the energy and material balance for the major process flows with inputs of one kilogram and one pound of feed, respectively. Although specific flows are shown, the process flow for a fixed feed rate will vary up to ±15 percent from the average process flow because of variations in the content of the solid waste. The energy and material balance was derived from average field data. All numbers in the balance were rounded off to reflect the appropriate accuracy. As is apparent in the balance, the kiln process is not a pure pyrolytic reaction but rather a substoichiometric combustion reaction zone. The heat transfer equations in a mathematical simulation of the kiln operation indicate that some *in situ* combustion of kiln-off gas is necessary to adequately process the solid waste in the kiln. (SYSTECH developed this model during its evaluation of the Baltimore plant to study alternative modes of kiln operation.)

The major material and energy inputs to the plant process are the solid waste boiler waters, and the combustion air introduced to various components in the processing system. The primary outputs from the process are steam generated by the waste heat boilers, flue gas discharged at the stack, and solid residue removed for landfill disposal. As derived from the energy balances, the net energy efficiency of the entire plant (energy input in waste/available energy output in steam) is about 40 percent. The available energy generated is the net energy supplied to the customer at the plant perimeter after in-plant steam use and losses have been accounted for. Energy losses from the plant processing equipment are primarily due to skin heat radiation and conduction and the heat lost in the flue gas discharge through the stack. Most of the energy in the electrical power supplied to the plant is dissipated to the atmosphere.

The solid, liquid, and gas emissions from the plant were evaluated in terms of their pollution potential. Although the plant is currently not environmentally acceptable, it will be after the equipment modifications and operational changes detailed in the following section have been made.

The particulate emissions in the gas discharged from the waste heat boilers are about 0.6 g/scm (0.26 gr/scf). This relatively large amount of emissions is due to the submicron particles emerging during the thermal processing. Although the low energy type wet scrubber employed at the prototype unit and the Baltimore plant performed at design efficiencies in both facilities, it could not reduce the emissions of the Baltimore plant to the Maryland limit of 0.07 g/scm (0.03 gr/scf). Since vendors have successfully demonstrated in extensive on site testing that a dry electrostatic precipitator can reduce the stack emissions to the prescribed limit, the wet scrubber is being replaced with a dry electrostatic precipitator.

The mass and volume of the incoming waste are reduced by 56 and 96 percent, respectively, which considerably reduces the landfill area required for the residue disposal. In addition to recovering energy and reducing the

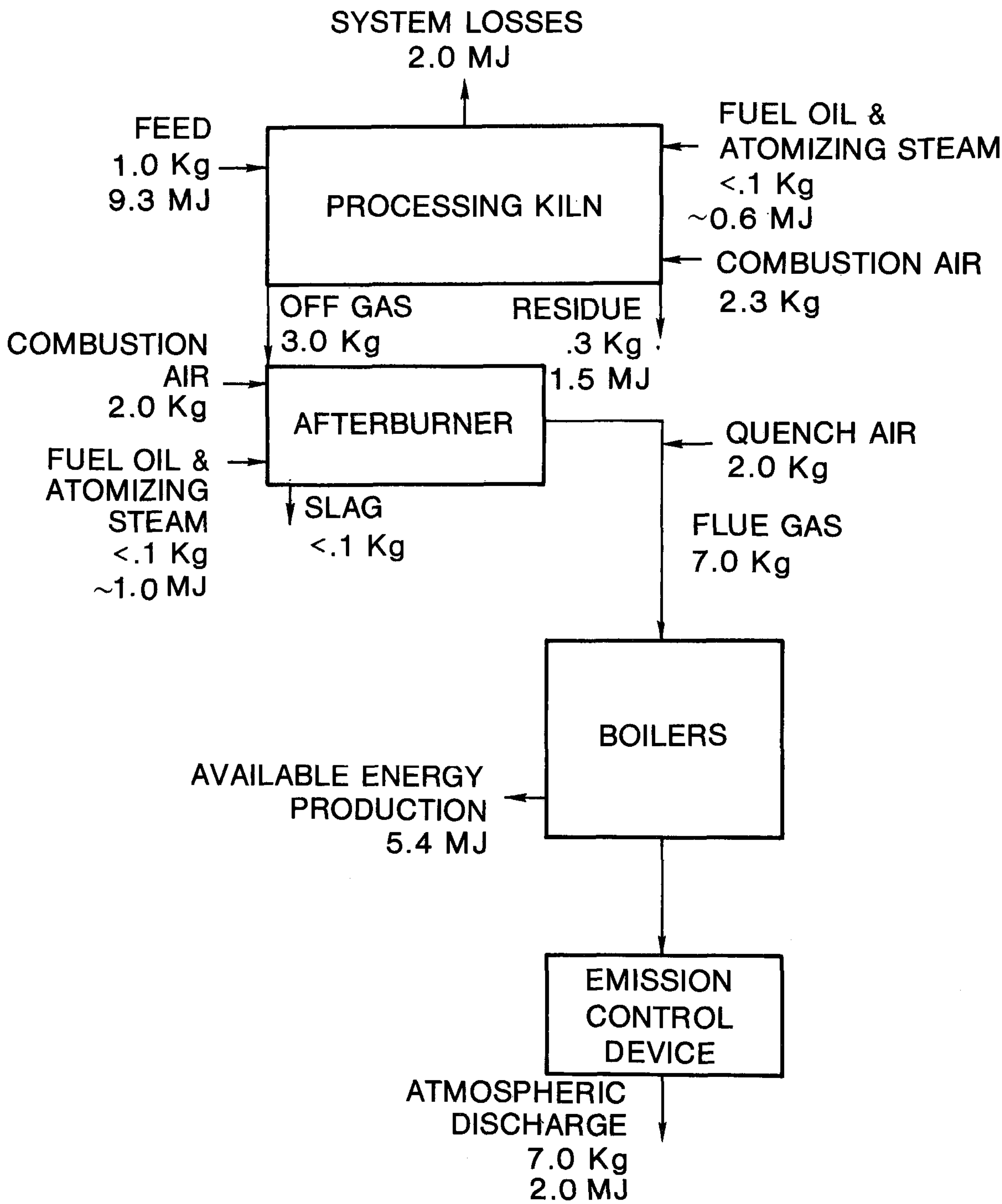

Figure 9. Process heat and material balance (SI units).

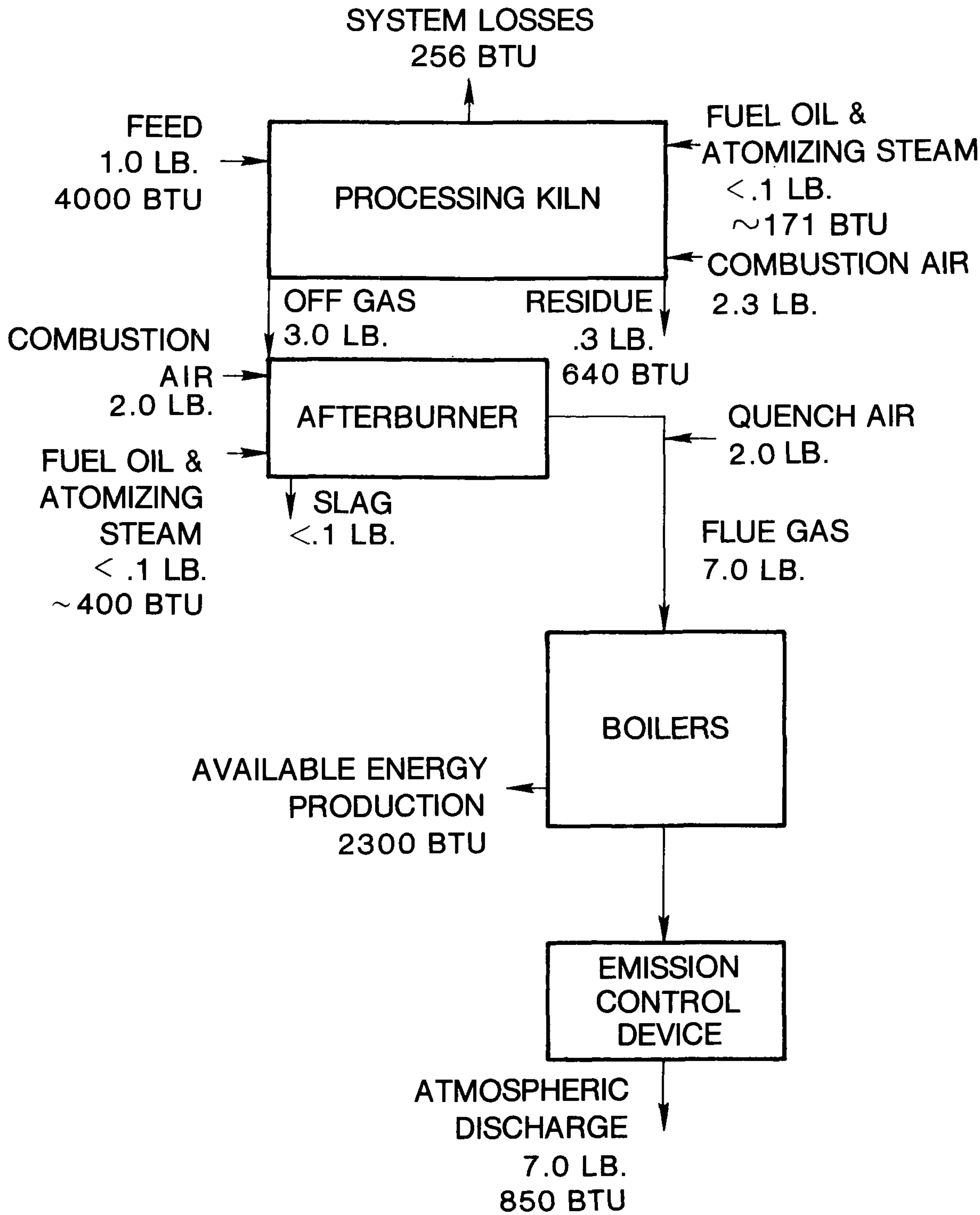

Figure 10. Process heat and material balance (English units).

quantity of waste to be disposed of, the plant processing reduces the waste to a relatively inert ash with a low putrescible content. Although heavy metals are among the solid residues, their solubility is reduced because of the alkaline characteristics of any leachate evolved from the residue. Wherever disposed of, this residue will have far less detrimental effects on the environment than unprocessed solid waste.

Only relatively "weak" wastewater consisting of city water, boiler blowdown, and water treatment discharge is presently discharged to the sewer. Most processing waters are in closed-loop lines and are only occasionally discharged to the ground when drain plugging or other equipment malfunctions occur. Such drainage should be treated before its discharge since it does not meet Federal water discharge quality standards and therefore, is environmentally unacceptable in the raw state. In addition, rain runoff carrying wastewater discharged to the ground will adversely effect the surface water quality in the plant area. However, if the processing water were discharged to the sewage system, it would have a negligible effect on the quality of the final effluent emitted from the wastewater treatment plant.

Fugitive emissions from the plant consist of dust and carbon monoxide. Although the effect of the microbes within the dust has not been determined, the dust concentrations have not risen above the nuisance level. During working hours, some areas of the waste receiving building have carbon monoxide concentrations greater than the threshold limit value (TLV) for continuous exposure. However, the building personnel have a limited exposure to these concentrations.

Noise throughout the plant is generally less than the OSHA level for an 8-hour exposure. While there are areas where the noise exceeds that level, the noise source varies and the duration of and exposure to the noise are intermittent.

Plant Modifications

Since the Baltimore plant has not operated as designed, it has been field modified extensively. The major modifications include the following: (1) replacing and upgrading the refractory linings in the kiln and ductwork; (2) installation of an explosion suppression system on the shredders; (3) redesign of the residue and slag handling conveyors; (4) introduction of a controlled-air combustion operational mode in the kiln; and (5) general improvements in the materials handling equipment. These modifications will be detailed in Section 2 of Volume II.

The cost to modify the Baltimore plant to date is summarized in the following table as the costs incurred under the "Supplemental Contract." As shown in the table, a substantial contingency fund would have been required to cover the field modification costs.

In addition to the above-mentioned modifications which were performed prior to Monsanto's termination, the following modifications are in progress: (1) redesign of the *gas purifier*; (2) replacement of the wet gas scrubber with a dry electrostatic precipitator; (3) elimination of the residue

TABLE 2. DEMONSTATION PROJECT FINANCING (TO FEBRUARY 1977)

Source	Original Contract		Supplemental Contract
Federal Grants	$ 6,000,000		$1,000,000
Md. Env. Service*	$ 4,000,000		
Baltimore City	$ 5,532,000		
Monsanto EnviroChem			$4,000,000
Subtotal	$15,532,000		$5,000,000
TOTAL		$20,532,000	

* No interest loan/grant.

separation module; (4) elimination of the storage and recovery unit; and (5) addition of a 220 foot stack. Based on the experience gained during the demonstration, these additional modifications being completed by the City of Baltimore are intended to bring particulate emissions into compliance with State regulations, to remedy deficiencies and malfunctions which caused previous plant downtime, and to simplify the overall plant operation.

While these modifications have a high probability of being successful, it is likely that they will reduce somewhat the thermal efficiency of the plant. However, if the modifications substantially increase the plant reliability, the plant should prove to be an economical means of disposing of municipal solid waste. Insofar as financing is concerned in the plant development, it must be noted that Baltimore has been in a more favorable financial position than a nondemonstration plant investor because of the outside agency subsidies that have defrayed the greater part of the total plant cost.

Cost Evaluation

The cost evaluation was intended to determine the net cost of operating the Baltimore plant in terms of the plant processing competitiveness with alternative systems for municipal solid waste disposal. Because of the erratic plant operation during the evaluation period from November 1976 through June 1977, and the extensive equipment modifications with the consequent extreme variation in the cost parameters, a cost evaluation was established for each of three scenarios (table 3). Arthur Young and Company, a subcontractor to SYSTECH, performed the cost evaluation according to EPA guidelines.*

Of the three scenarios, the first reflects the plant operating conditions during the 6 months from November 19, 1976, to May 1977 the period during the evaluation of maximum material throughput.† The second and third scenarios are based on the projected plant operations when the proposed equipment modifications and improved operating procedures will have been implemented. The second scenario represents reasonably expected conditions, and the third optimum conditions. Consequently, the three scenarios provide the means for making comparisons to assess the potential value of the plant and to determine which plant changes can be justified from the standpoint of efficiency and cost.

Plant capital costs were determined from the City of Baltimore extract listing and a Monsanto EnviroChem report§ detailing the pertinent expenditure invoiced in the city Listing. The capital costs were adjusted to discount the one-time costs associated with the first-of-a-kind demonstration. The adjusted capital cost was $21,960,000. Then, assuming financing by a Baltimore bond issue, the cost was depreciated over a 20-year plant life to arrive at a "nondemonstration" annual cost.

Net operating and maintenance costs were computed by combining actual operating data with the projected operating schedule. After deriving operating costs from actual field-measured quantities calculated on a per ton basis, the costs were applied to the respective operating schedules and throughput capacities to determine annual operating costs. Similarly, steam revenues were derived on an annual basis from operating data applied to each schedule. Because of the limited and sporadic on-stream time and consequent varying maintenance requirements, 5.5 percent of the capital cost was used to arrive at the annual maintenance costs. This percentage was based on IRS guidelines and the experience of similar processing plants.

Then for each scenario (table 4), the annual capital, operating, and maintenance costs were divided by the annual throughput rate of the plant to yield the total operation costs on a dollar per ton basis. Given its performance to date, the Baltimore plant cannot compete economically with a system disposing of municipal solid waste by other methods. The current net operating cost, including total depreciation and interest, for the Baltimore plant exceeds $64 per Mg ($58 per ton) of waste input. Because of Baltimore's unique financial arrangement in the plant development, the actual cost to the city is about $35 per ton. However, since the proposed plant modifications and better operating procedures will substantially increase the plant throughput and correspondingly decrease the cost to process a ton of solid waste,

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* Sussman, D. B., Resource Recovery Plant Implementation Guides For Municipal Officals, Accounting Format. EPA publication SW-157.6.

† From February 1977 to January 1978, the plant disposed of 68,000 tons of solid waste and generated 263,000,000 pounds of steam.

§ Buss, T., Number 9 Report, Monsanto Corporation Unpublished Report.

TABLE 3. SCENARIO OPERATING PARAMETERS*

	Scenario 1	Scenario 2	Scenario 3
Operating schedule:	24 hr/day, 6 days/week, 24 shutdowns/yr	24 hr/day, 7 days/week, 8 shutdowns/yr	24 hr/day, 7 days/week, 4 shutdowns/yr
Operating status (days):			
Normal processing, †	104	264	312
Standby, §	56	21	18
Heating and cooling, ¶	48	16	8
Downtime, **	157	64	27
Refuse feed rate:			
Mg/hr	27	32	36
Mg/yr	67,000	203,000	270,000
Steam production (kg/hr):			
Normal processing	50,000 (2/3)	59,000 (2/3)	66,000
	35,000 (1/3)	35,000 (1/3)	---
Standby	35,000	35,000	35,000
Staffing:			
Plant manager	1	1	1
Plant supervisor	1	1	1
Clerk typist	1	1	1
Chief operators	5	4	4
Field operators	5	12	8
Ram operators	3	--	--
Equipment operators	3	4	4
Laborers	5	7	5
Scalemen	1	1	1
Engineers	--	1	1
Laborers/chauffeurs	7	5	4
Maintenance supervisor	1	1	1
Electricians	2	2	1
Mechanics	3	6	4
Welders	2	1	1
Oilers	--	1	1
Instrument technicians	--	1	1
Total staffing	40	49	39
Fuel consumption (ℓ/hr):			
No. 2 fuel:			
Normal processing	660	660	660
Standby	3,260	3,260	3,260
Heating and cooling	1,960	1,960	1,960
Downtime	0	0	0

TABLE 3. (Continued)

	Scenario 1	Scenario 2	Scenario 3
Gasoline:			
Normal processing	620	620	620
Standby	620	620	620
Heating and cooling	93	93	93
Downtime	93	93	93
Diesel fuel:			
Normal processing	208	208	208
Standby	208	208	208
Heating and cooling	64	64	64
Downtime	64	64	64
Electricity consumption (kw):			
Normal processing	2,100	2,100	2,100
Standby	1,109	1,109	1,109
Heating and cooling	1,109	1,109	1,109
Downtime	142	142	142
Water consumption (ℓ/day):			
Normal processing	1,595,380	1,835,140	2,021,620
Standby, ††	1,195,780	1,195,780	1,195,780
Heating and cooling	187,780	187,780	187,780
Downtime	187,780	187,780	187,780
Sewer flow (ℓ/day):			
Normal processing	395,380	419,140	437,620
Standby	355,780	355,780	355,780
Heating and cooling	187,780	187,780	187,780
Downtime	187,780	187,780	187,780

* Provided by SYSTECH.

† Constitutes processing of waste.

§ Constitutes onstream with no processing of waste.

¶ Involves startup and cool-down of kiln.

** No activity, plant shut down.

†† 35 Mg/hr of steam.

TABLE 4. PROJECTED COST SUMMARY*

	Scenario 1†		Scenario 2§		Scenario 3¶	
	($/Mg)	($/ton)	($/Mg)	($/ton)	($/Mg)	($/ton)
Capital costs	$22.60	$20.50	$ 7.70	$ 7.00	$ 5.90	$ 5.30
Interest	14.10	12.80	4.80	4.30	3.60	3.30
Operating and maintenance costs	42.00	38.10	14.60	13.30	11.00	10.00
Total Costs	78.70	71.40	27.10	24.60	20.50	18.60
Revenues	14.60	13.20	10.70	9.70	12.70	11.50
Net Cost	64.10	58.20	16.40	14.90	7.80	7.10

* In 1977 dollars

† Annual throughput is 67,000 Mg/yr (74,000 tpy)

§ Annual throughput is 203,000 Mg/yr (223,000 tpy)

¶ Annual throughput is 207,000 Mg/yr (300,000 tpy) reasonable projections indicate that the Baltimore plant can become economically viable.

SPECIFIC PROBLEM AREAS

Since the Baltimore plant has not operated as designed, much of the plant evaluation has been devoted to determining what works and what does not. When this review revealed that a system component or procedure definitely failed or was ineffective, the next step was to analyze the reason for its failure or deficiency. All malfunctions, failures, and shutdowns during the demonstration are detailed in the second volume of this report. In volume IV of the evaluation, an in-depth analysis of some of the more critical design deficiencies is presented.

The following paragraphs of this section deal with some of the major problems that caused plant shutdown or seriously interfered with efficient operation. These problems are grouped under four headings: (1) Scaling from Prototype to Large-Scale unit, (2) Variation from the Design of Proven Systems, (3) Designing for Heterogeneous Municipal Solid Waste, and (4) Project Management. Among the specific subjects included are kiln performance, gas purifier reliability, stack emissions control, and material handling.

Scaling from Prototype to Large-Scale Unit

The following account of the rotary kiln performance and its effects on the local and downstream equipment and operations highlights the criticalness of engineering when scaling from a prototype to a large-scale unit.

In retrospect, the basis for scaling was inappropriate since the combined aerodynamic and thermodynamic factors changed during the scale-up. As a result, the kiln process was unstable, and the kiln temperatures have been 337C (630F) above the design level. With the instability causing fluctuations in process temperatures of 150C (300F) over a 20-minute period, it was virtually impossible to control the process. Consequently, the residue discharged from the kiln ranged in quality from fused slag balls 1.2 meters (4 feet) in diameter to slightly burned paper. Such extremes in the residue quality caused the discharge conveyor to be overloaded and the kiln to be shut down on many occasions.

In addition to the high and fluctuating process temperatures, faulty refractory installation techniques and the differential thermal expansions in the kiln shell caused severe refractory failures in the kiln. However, a new method for introducing air into the kiln, upgraded refractory with a better installation technique, vessel skin cooling, and expansion slots inserted at the vessel ends have virtually eliminated the refractory failures.

The vaporization of metals in the kiln is also attributed to some degree to the excessive process temperatures. In the *gas purifier*, the metals in the kiln-off gas reoxidize and condense, and most of the fine particles remain entrained in the cooled gas discharged to the wet gas scrubber. Then, since the scrubber has not efficiently removed the very small metal particles as well as larger particles from the flue gas, it cannot attain the emission levels of the prototype scrubber. In addition, since the gas scrubber is upstream of the induced draft fan, the condensed acids in the flue gas have corroded the fan blade. Moreover, solids have so accumulated on the impellers that the fan has vibrated excessively. Consequently, the fan was shut down weekly for the 3 to 5 days needed to sandblast and rebalance the fan.

The scrubber-related problems have been remedied temporarily by radically reducing the water flow to the scrubber, and will be solved permanently by replacing the wet scrubber with a dry electrostatic precipitator.

Conclusion: Large magnitude scaling can be dangerous. Perform sufficient testing to validate scaling factors, and install sufficient excess capacity and flexibility to compensate for variations from design.

Variation from the Design of Proven System

The experience with the *gas purifier* illustrates the importance of identifying and analyzing the implications of any variation from the design of a proven system. In this instance, the design variation was from the non-slagging mode of the prototype to the slagging mode of the *gas purifier* in the Baltimore plant. The following account of the problems with the *gas purifier* reveals the inadequate understanding and implementation of the provisions needed for the *gas purifier* operational mode.

During the demonstration, the plugging of the slag tap hole at the bottom of the *gas purifier* caused extensive downtime. As the molten slag passed through the hole, it was chilled by the water quench at the bottom of the hole. Then the chilled slag solidified and built up on the edges of the hole in layers until the entire hole was plugged, shutting down the processing system to allow clearing the hole which took 7 days on the average. Consequently, to maintain a continuous flow of slag through the hole, the temperature in the *gas purifier* had to be increased to 1380C (2500F) which is 260C (500F) above the design temperature. But the increased temperature coupled with the corrosiveness of the molten slag caused frequent refractory failures in the *gas purifier*.

Conclusion: Extreme care must be exercised in making changes from the tested design. Anticipate problems and provide flexibility in the design in areas where changes have been made.

Designing for Heterogeneous Municipal Solid Waste

The lack of sufficient information and conservative design have caused many problems and shutdowns in the material handling equipment. The characteristics of mixed municipal solid waste must be thoroughly researched before initiating the design for the material handling equipment. This type of waste is extremely heterogeneous with time-varying characteristics of particle size, bulk densities, and moisture content. Consequently, the material handling equipment must be overdesigned with provisions to anticipate the variations in the waste characteristics. At the Baltimore plant, much of the material handling equipment had to be abandoned or required redesign as the result of this condition.

Such variations in the waste characteristics coupled with deficiencies in the material handling equipment have caused operational difficulties, equipment jams, system shutdowns, excessive wear, and abandonment of some equipment. For example, compacted waste in the silo storage and recovery system caused severe operational difficulties and such excessive wear that operation of that system had to be discontinued. Compacted waste in the ram hydraulic feeders frequently became so jammed that the waste could not be extruded into the kiln until the system was shutdown and the waste cleared away. Large agglomerations of fused slag have jammed both the kiln and the gas purifier residue conveyors to the point where the process had to be shutdown. Other equipment jams, such as those on the residue conveyor to the materials recovery building, have been due to the binding effect of wires and stringy materials. In addition, frozen and low density waste sliding on the inclined conveyors have hampered the operating process.

Conclusion; Solid waste is a heterogeneous material having widely varying characteristics. To successfully handle or process this material, the equipment design must allow for the variations in size, moisture content, and density of the material handled.

Program Management

The review of the direction and administration of the project stressed the need for a unified organization when a large-scale scientific-engineering developmental program is undertaken. The following summary of the demonstration management indicate, that despite the generally common interests and professional integrity of the participants, the circumstances did not allow the formation of such an organization.

Four agencies were involved in the demonstration: The City of Baltimore, State of Maryland, Monsanto EnviroChem, and U.S. EPA. While all worked toward the successful performance of the demonstration, their particular interests, responsibilities, and orientation differed widely. As noted earlier in this section, any decision-making had to be approved in a varying chain relationship by the City of Baltimore, Monsanto, and EPA. Consequently, their varying interests and perspectives caused delays, especially in the plant shutdown periods, and hampered plant operation and administrative functions.

During the startup, organizational and operational complications arose in defining the roles and responsibilities of personnel. While the City of Baltimore provided the personnel for the plant operation, maintenance, and administration, Monsanto EnviroChem provided the personnel for engineering support. Monsanto's services consisted of offering technical recommendations for the plant operations and supervising the plant operators. At the outset, Monsanto had to increase the number of its onsite engineers. At the conclusion of the demonstration, the entire Monsanto team withdrew from the site without a similarly qualified group from the city organization to take its place. The Baltimore project engineer assigned to the demonstration was not intended to continue his plant position after the program was completed. In addition, three of the management personnel at the plant resigned during the demonstration, and were not be replaced with similarly qualified personnel because of a city hiring freeze.

During the startup, the plant manager had limited authority over plant operation because of the assignment of a project engineer who transmitted information directly between Monsanto and the Head of the Department of Public Works. Normally, the downward chain of command from the Head of the Department of Public Works is to the Head of the Sanitation Division, to the Incinerator Chief, to the plant manager. Consequently, bypassing the Head of the Sanitation Division and the Incinerator Chief, precluded their normal function and service as well as their support of the plant manager.

Still other impediments to the efficient performance of the demonstration were the city's procurement and accounting systems. According to established practice, the city's procurement office required a minimum of 2 weeks to process a purchase order. However, after the city took over the operation of the plant, a more timely processing of the plant's purchase orders occurred. The city's accounting system was structured for expenditures in typical routine city operations but not for the unique transactions required for the plant operation. Consequently, it was very difficult during the demonstration evaluation to use the accounting system records in determining the cost trade-offs, the system operational efficiency, and the actual cost of the solid waste processing.

Conclusion: An inadequately integrated organizational structure can be an impediment to efficient project execution. Responsibility for plant startup and demonstration of new resource recovery processes should be assigned to the system designer, with the transfer to the normal operating staff <u>after</u> acceptance.

SUMMARY

From the viewpoint of the Monsanto EnviroChem, the demonstration was unsuccessful. But to the U.S. EPA, SYSTECH, and the resource recovery industry in general, the demonstration achieved most of the desired results. The particularly useful results were (1) the thorough investigation of the Landgard process; (2) the invaluable trial-and-error experience to prevent future costly but ineffective innovations; and (3) the development of significant equipment and operational procedures, notably the rotary kiln.

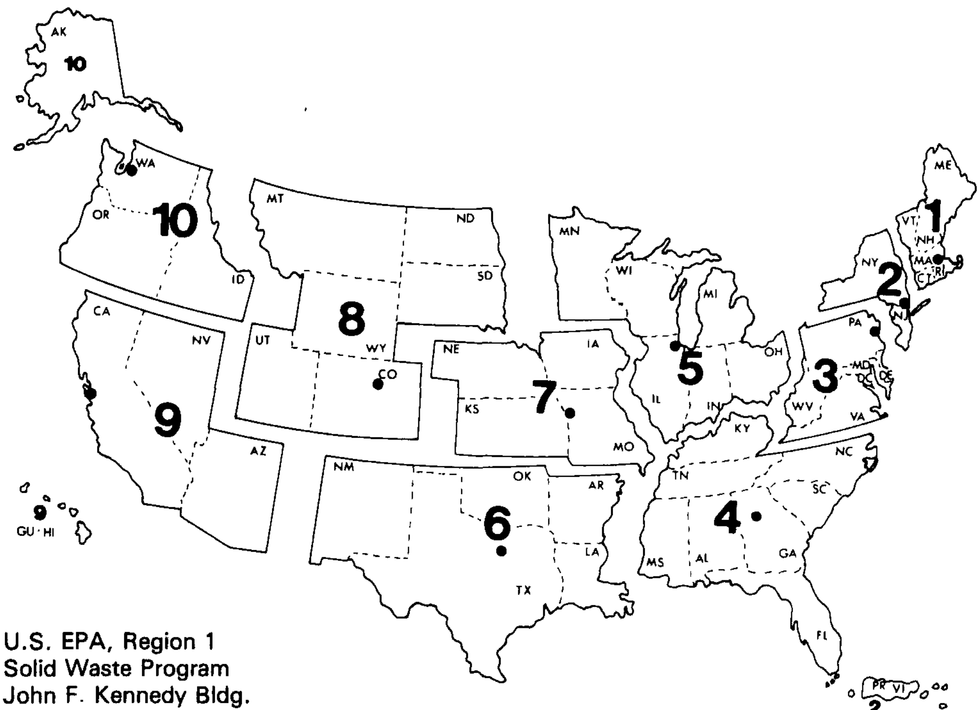
The rotary kiln has proved to be an excellent primary reaction vessel after its evolvement and conversion from a pure pyrolytic reactor to a substoichiometric combustion reactor. In addition, the demonstration proved the feasibility of utilizing the system concept for heat recovery from municipal solid waste. Moreover, while the kiln is definitely competitive with other similar commercial processing systems, it has the potential, when combined with heat recovery, for being economically competitive with direct raw waste-to-landfill operations. The fulfillment of this potential depends primarily on developing auxiliary system components with the degree of reliability normally attained in other types of commercial processes.

In addition to the invaluable experience gained and the various contributions to the state of the art, the demonstration and its subsequent evaluation has revealed the critical importance of the following: (1) conducting exhaustive theoretical and empirical research before scaling from a prototype to a large-scale facility; (2) identifying and analyzing the effect of any variations from the design of a proven system; (3) designing material handling and processing equipment with provisions for surge capacities and equipment-weather contingencies in view of the heterogeneous content of municipal mixed solid waste with its time-varying characteristics; and (4) ensuring that the program management is an integrated organization with the efficiency and common objectives required for a large-scale scientific-engineering development.

Reasonable projections indicate that the proposed modifications and improved operating procedures will make the Baltimore plant economically viable.

In any event, the rotary kiln potential should be further exploited by conducting additional theoretical studies to characterize and optimize kiln operating conditions and by replacing malfunctioning auxiliary equipment with the purpose of (1) improving the system reliability, (2) simplifying the overall process, and (3) reducing capital and operating costs.

EPA REGIONS



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